Monitoring Atmospheric CO_2 from Space: Challenge & approach

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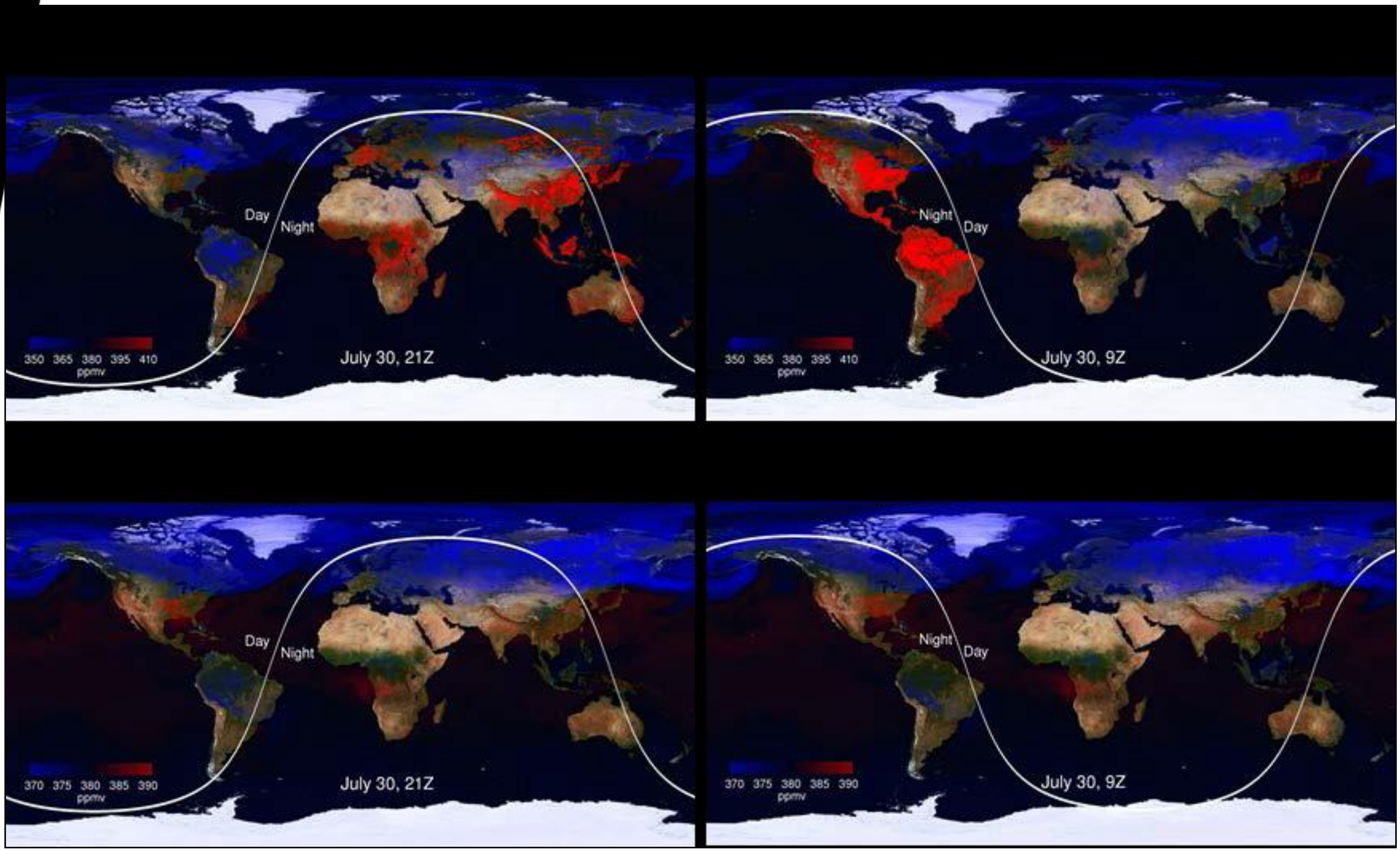
The 4th International Symposium on Atmospheric Light Scattering and Remote Sensing
1-5 June 2015, Wuhan, China

Outline

- **Introduction**
  - Carbon sciences and challenges
  - Lidar CO_2 measurement approach
  - Instrumentation
- **Lidar Measurements**
  - CO_2 column measurements
  - Accuracy and precision
  - CO_2 column measurements with clouds
  - Ranging measurements
  - Space application
- **Summary**

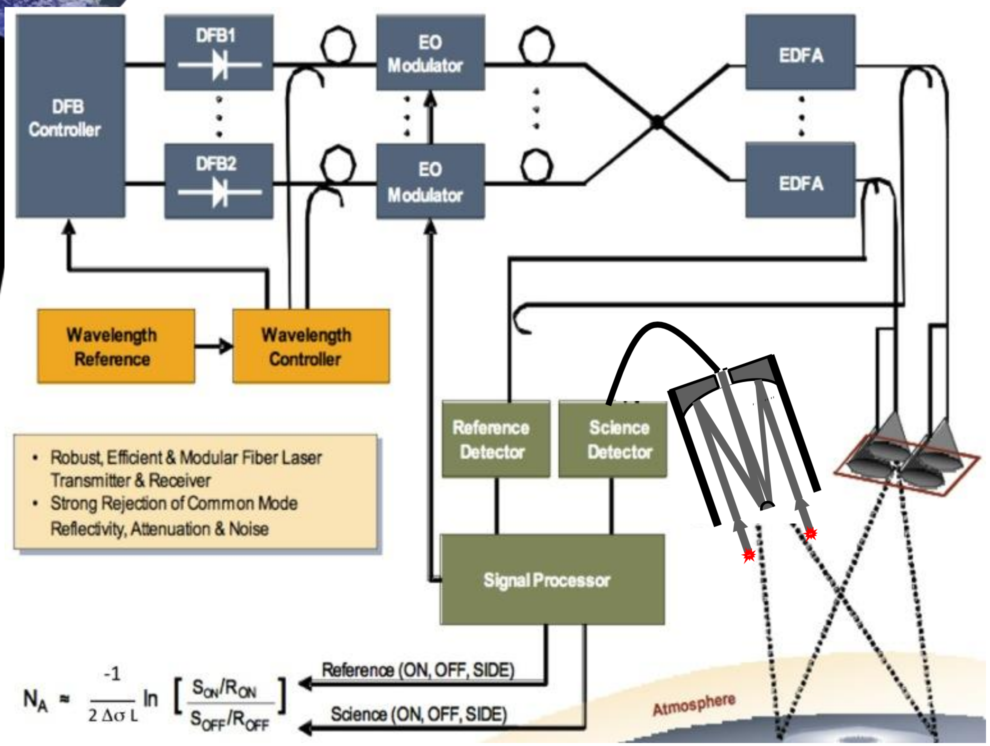
Grand Challenge: small changes
(GEOS-5 Simulated XCO_2 : Day vs Night)

July 30, 21 Z **July 30, 9 Z**

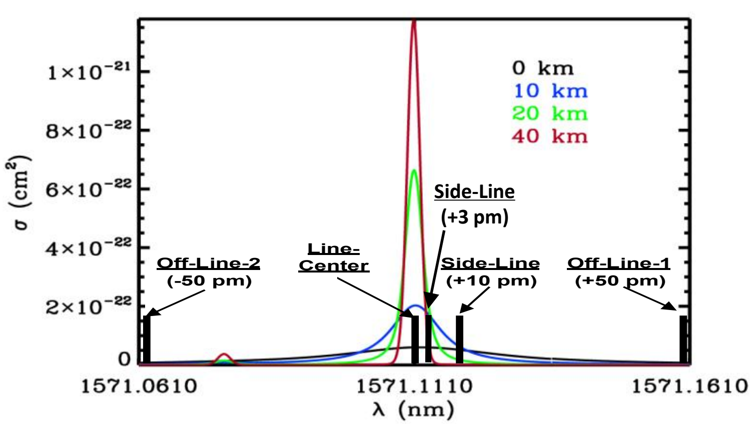


upper: surface XCO_2; lower: column averaged XCO_2

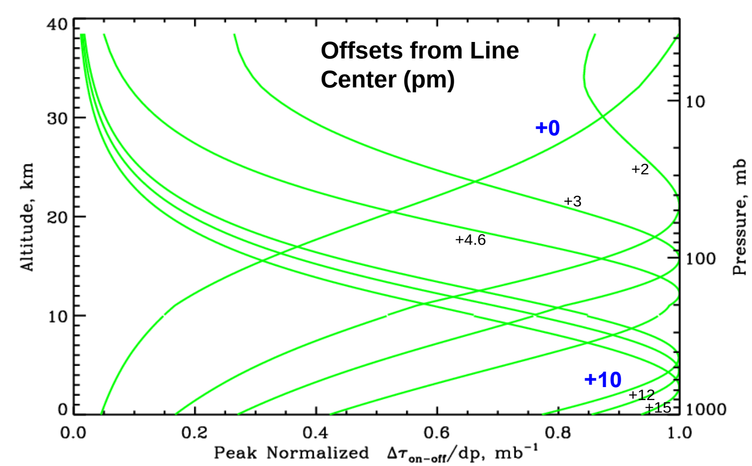
CO_2 Measurement Architecture
IM-CW Laser Absorption Lidar



- Simultaneously transmits λ_{on} and λ_{off} reducing noise from the atmosphere and eliminating surface reflectance variations.
- Approach is independent of the system wavelength and allows simultaneous CO_2 & O_2 (1.26 μm) measurements for deriving XCO_2 measurement.



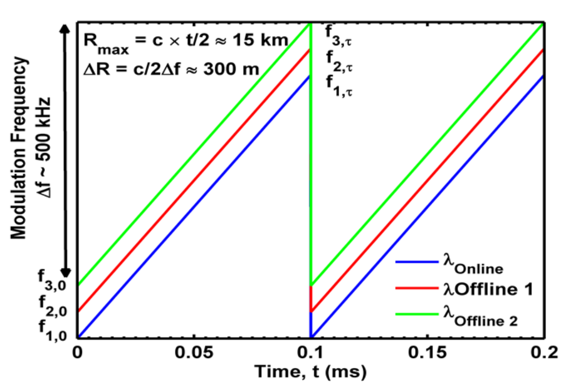
Weighting Functions



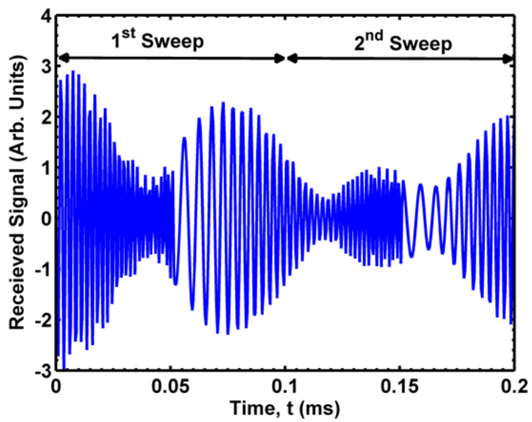
IM-CW Laser Absorption Lidar 1.57-µm CO_2 Measurement Technique

Progression of Transmitted/Received Intensity-Modulated Waveforms

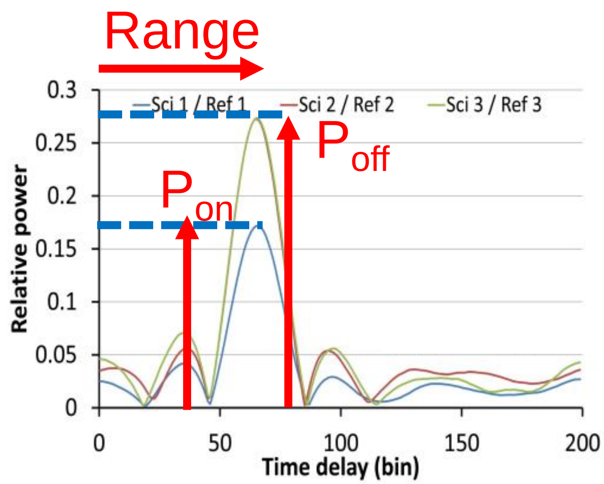
Simultaneously transmitted Intensity modulated range encoded waveforms



Simultaneously received Online and Offline IPDA returns



Measurement: Output of correlation between transmitted and received waveforms



Range encoded approach for detection and ranging is analogous to mature CW Radar and GPS measurement techniques

$$DAOD = \frac{1}{2} ln \left(\frac{P_{off} * E_{on}}{P_{on} * E_{off}} \right)$$

Instrument Development

(Langley and Exelis; 14 MFLL + 1 ACES campaigns)

ASCENDS CarbonHawk Experiment Simulator (ACES; developed at Langley with support from Exelis)

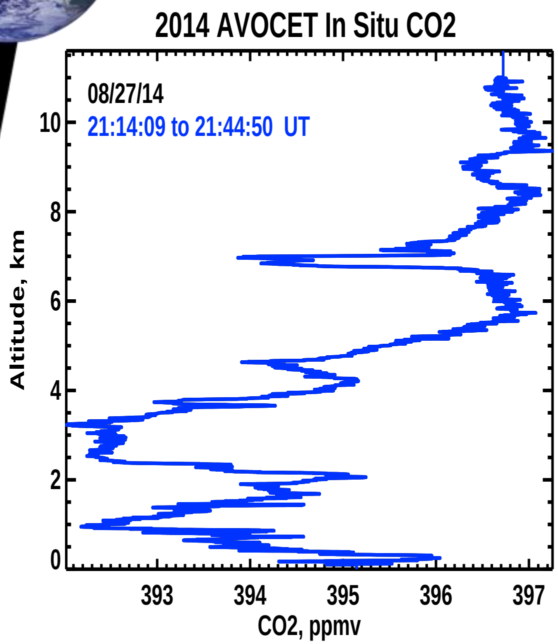
3×10W amplifier integration

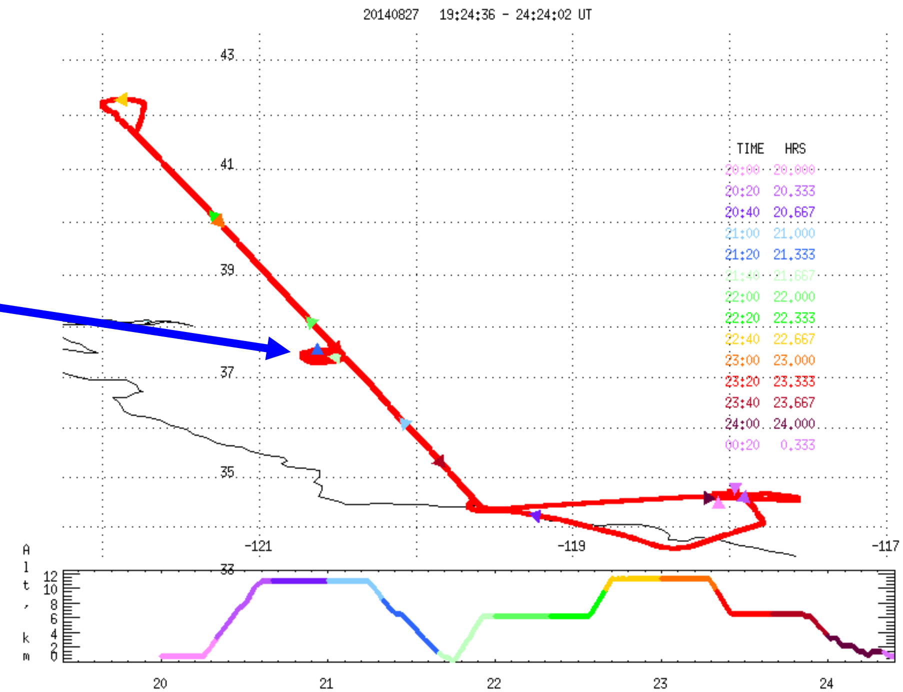
Multifunctional Fiber Laser Lidar (MFLL) (developed by Exelis in 2004 Exelis and Langley since 2005)

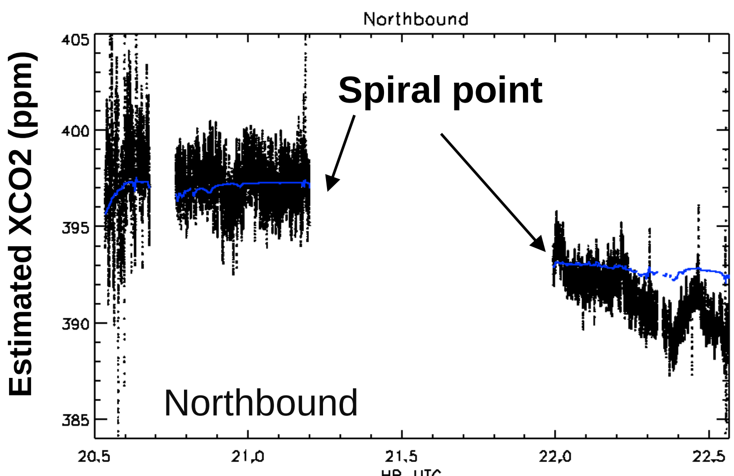
Instrument-aircraft integration

advancing key technologies for spaceborne measurements of CO_2 column mixing ratio

In Situ and Lidar Comparision
(MFLL OCO-2 Under Flight: 20140827)







Black curves: lidar measured XCO2
Blue curves: in-situ derived XCO2

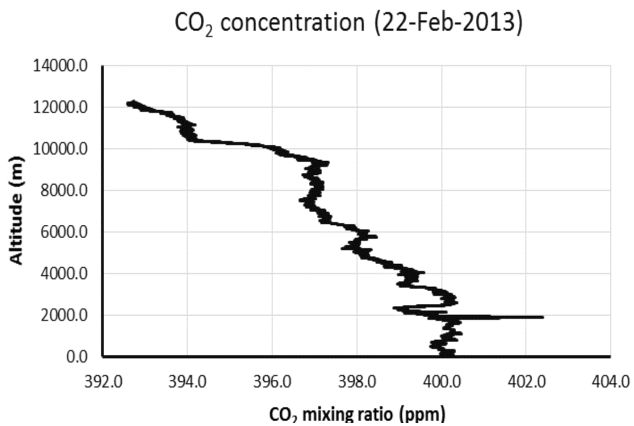
In-situ derived (or modeled) Value

- In-situ from Spiral: XCO_2, T/p/q profiles
- Radiative transfer model
- Ranging correction with lidar range data
- In-situ derived (or modeled) DAOD
- In-situ derived (or modeled) XCO_2

difference (ppm): 0.18

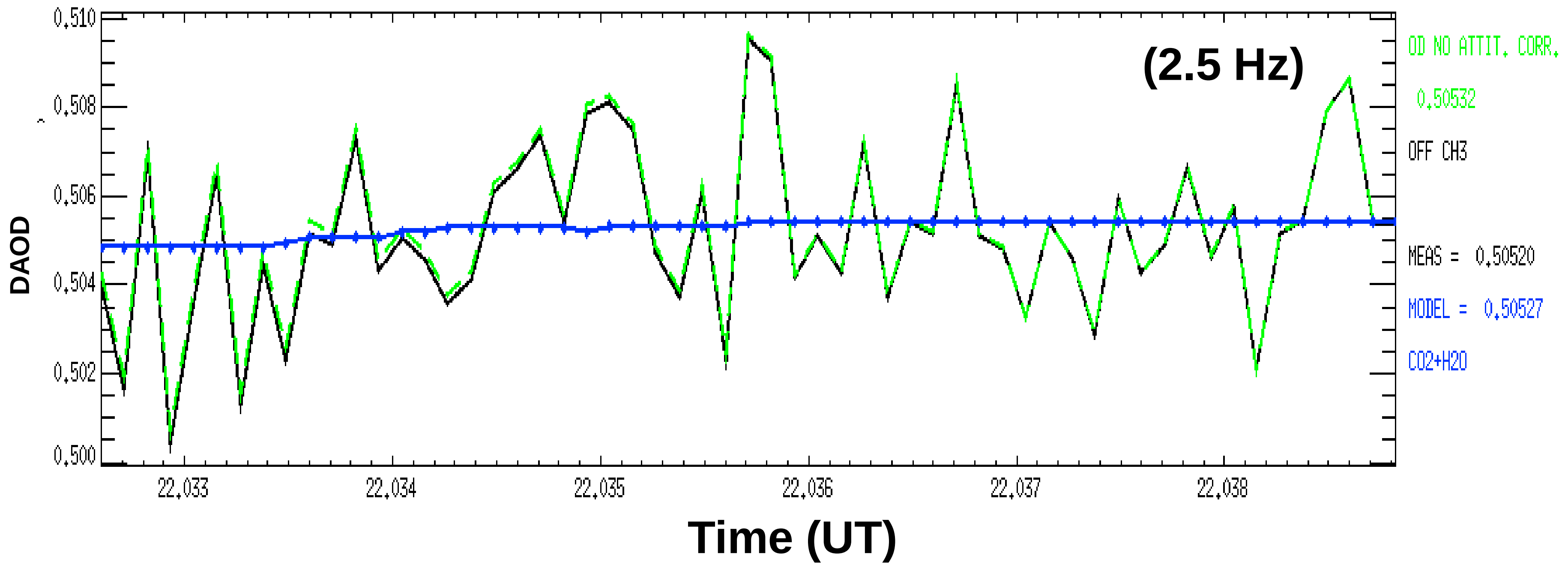
Winter 2013 Flight Campaign

(22 Feb. 2013 Flight: Blythe, CA)



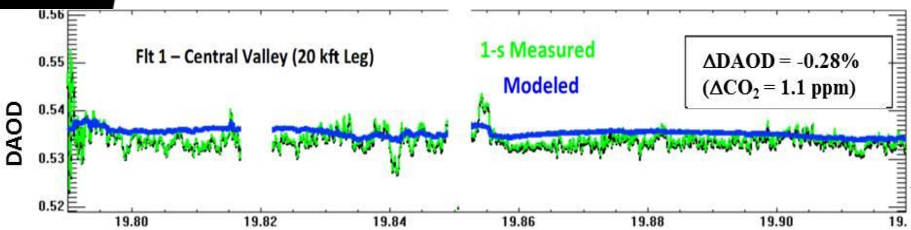
Comparison of CO_2 columns from MFLL measurements and in situ derived values

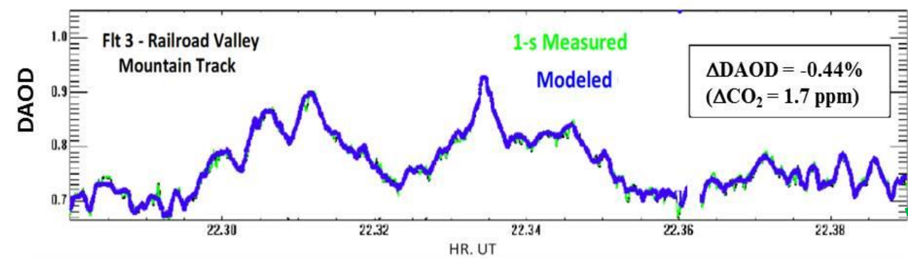
$(DAOD_{mea} – DAOD_{mod})/DAOD_{mod}$ = - 0.01% (or within 0.04 ppm)

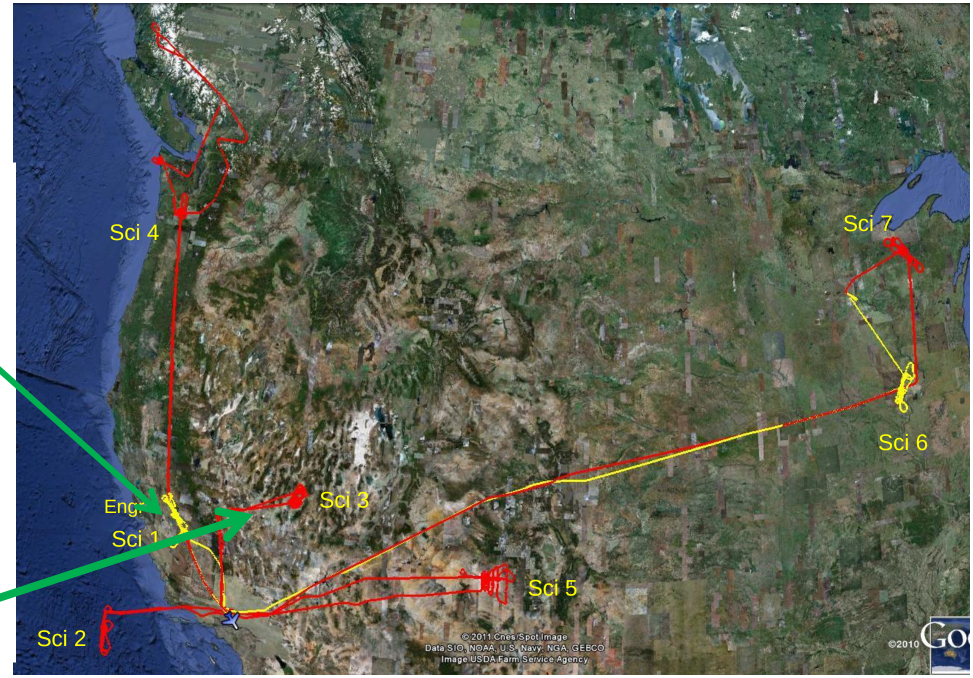


2011 ASCENDS DC-8 Flight Campaign (MFLL during 28 July – 11 August)

Differential Absorption Optical Depth (DAOD) Comparisons







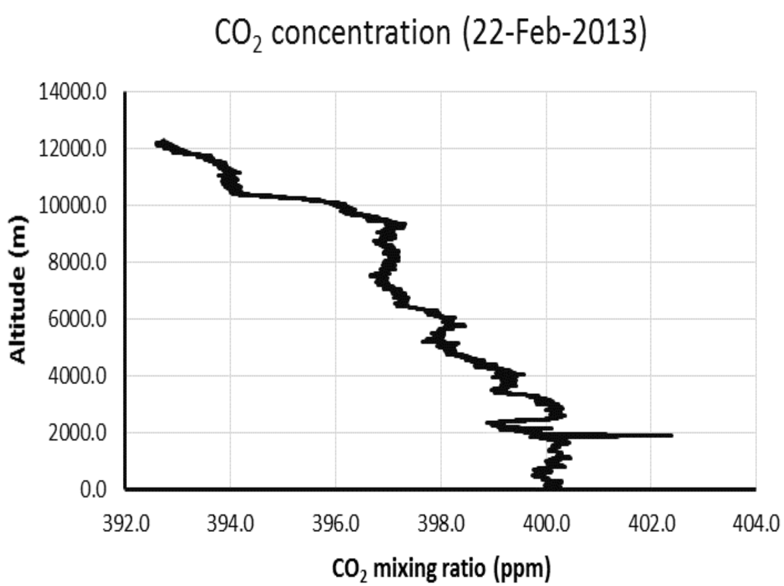
SNR Comparisons

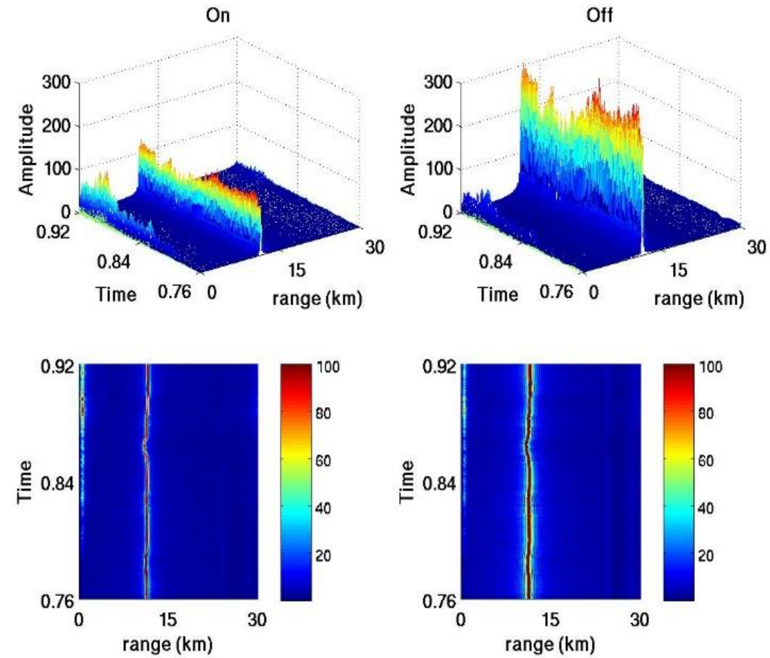
Flight #	Start Hour	End Hour	Delta Time, sec	Nadir Range, m	Optical Depth	CO2, ppmv	1-s SNR	1-s ! , ppmv	10-s SNR	10-s ! , ppmv
1	20.07	20.08	198.0	6406	0.708	389.7	433	0.90	1264	0.31
3	20.03	20.06	211.0	6593	0.755	394.5	517	0.76	1510	0.26
4	15.63	15.70	396.0	6360	0.704	387.1	460	0.84	1325	0.29
5	20.00	20.02	180.0	8063	0.924	391.8	418	0.94	1274	0.31
7	17.21	17.23	79.2	5805	0.632	379.2	396	0.96	1237	0.31

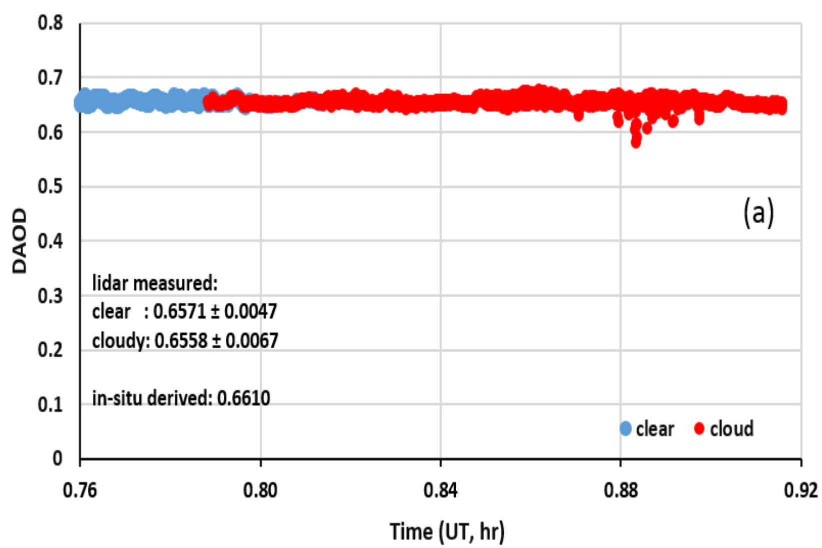
Avg:	6645	0.745	388.5	445	0.88	1322	0.29

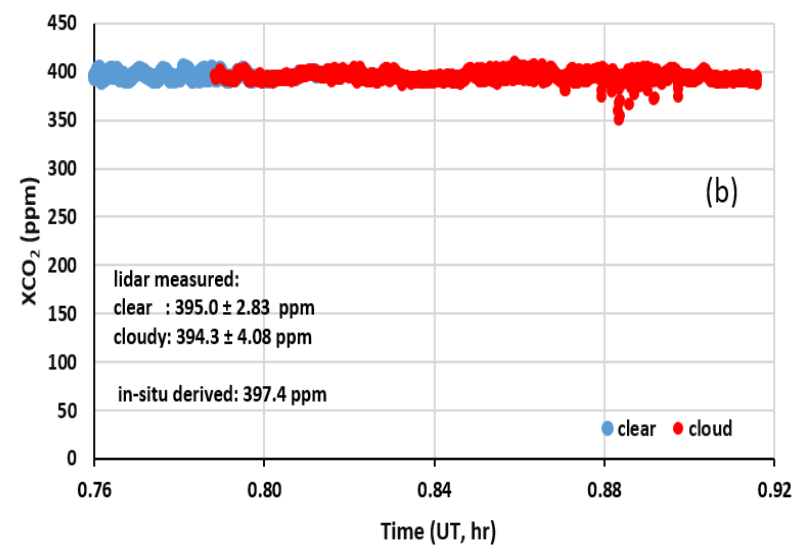
Modeled DAOD: in-situ XCO2 measurements + radiative transfer model to calculate CO2 absorption optical depth

MFLL CO_2 Column Measurements Through Thin Cirrus (22 Feb 2013)









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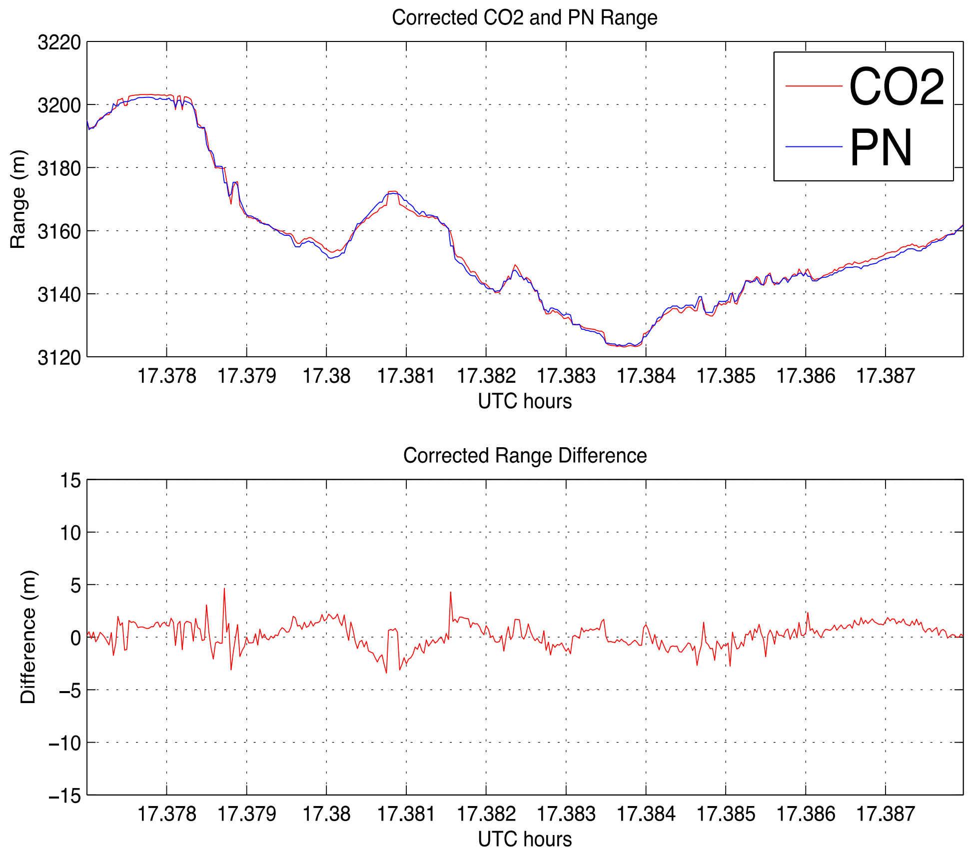
Comparison of Range Determination from PN Altimeter and Off-line CO_2 Signal



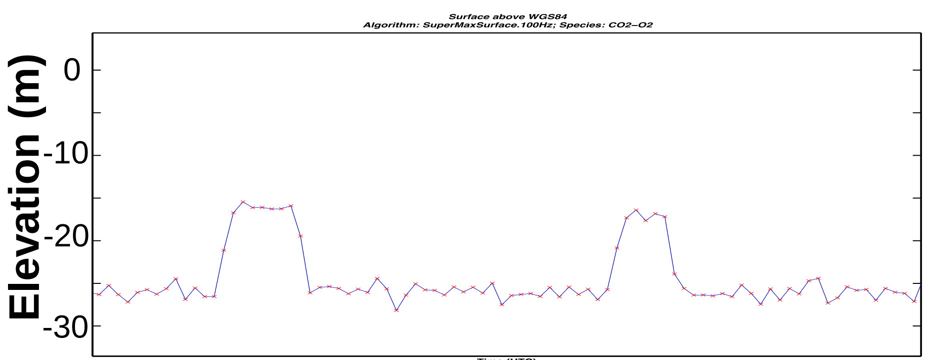
MFLL

RMS errors < 3 m

Range estimates obtained from the off-line CO_2 return and time coincident returns from the onboard PN altimeter over the region of Four Corners, NM from the DC-8 flight on 7 August 2011.

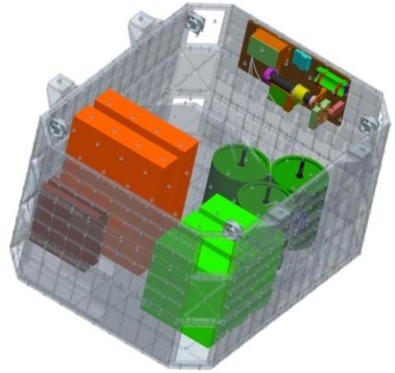
Ranging over Hampton Roads
(ACES in June 2014)

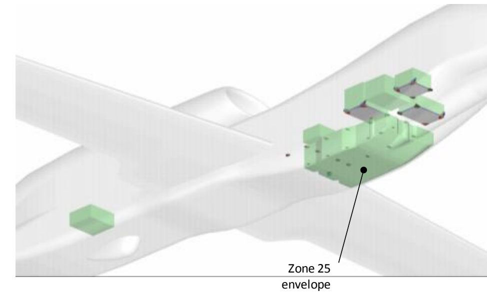
Chesapeake Bay Bridge



ASCENDS Mission Development

Current





Today: MFLL and ACES instruments in DC-8 racks

Global Hawk

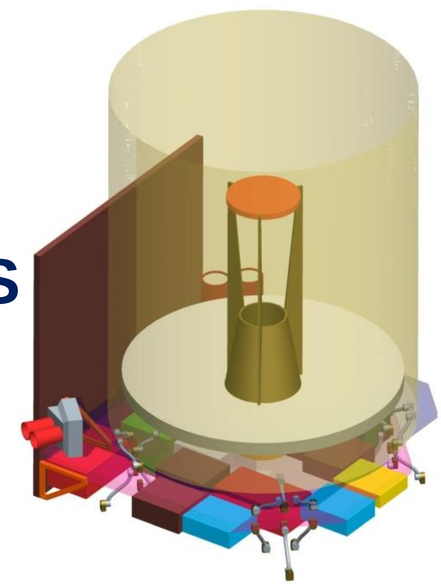
Size = 100” x 43” x 24”
Mass = 787.2 lb.

Size = 44” x 34” x 24”
Mass = 317.1 lb

Future

TBD:
ISS Tech Demo?

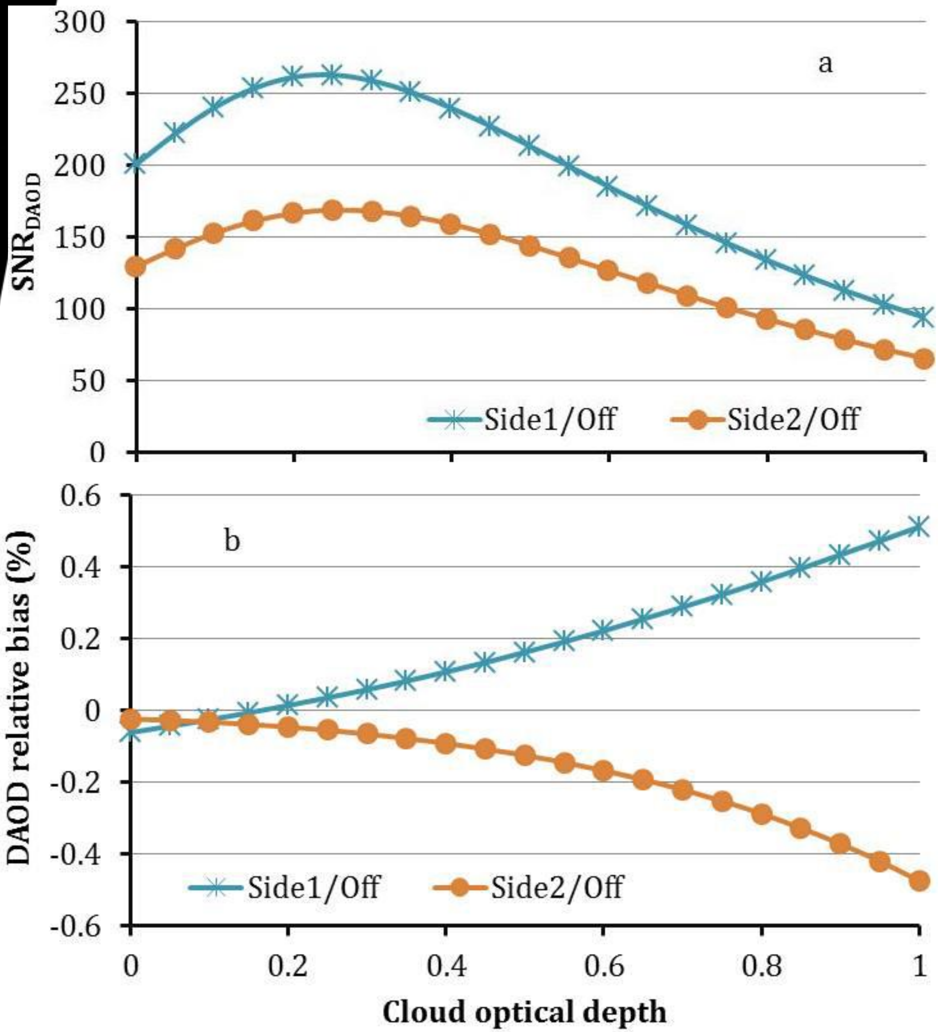
TBD:
ASCENDS mission

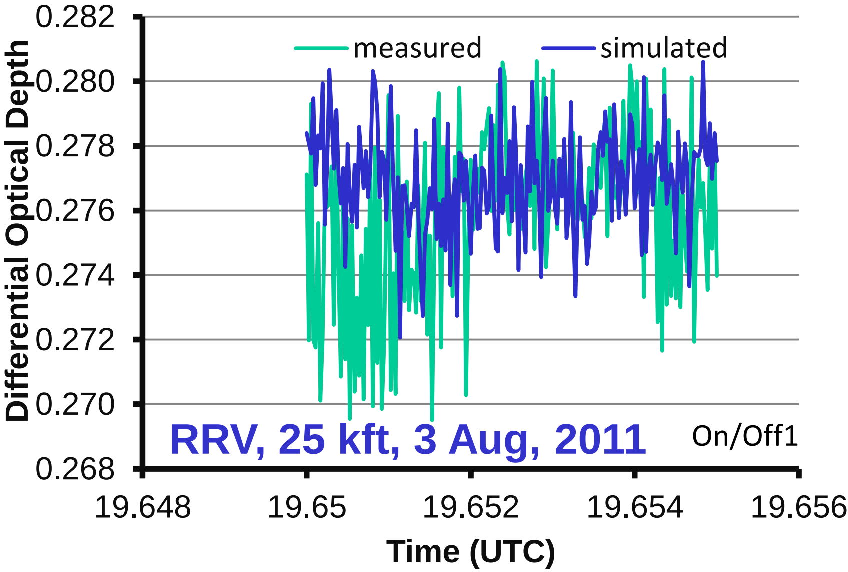


Space CO_2 Lidar Modeling and Measurement

ASCENDS

same instrument architecture: increased power and telescope





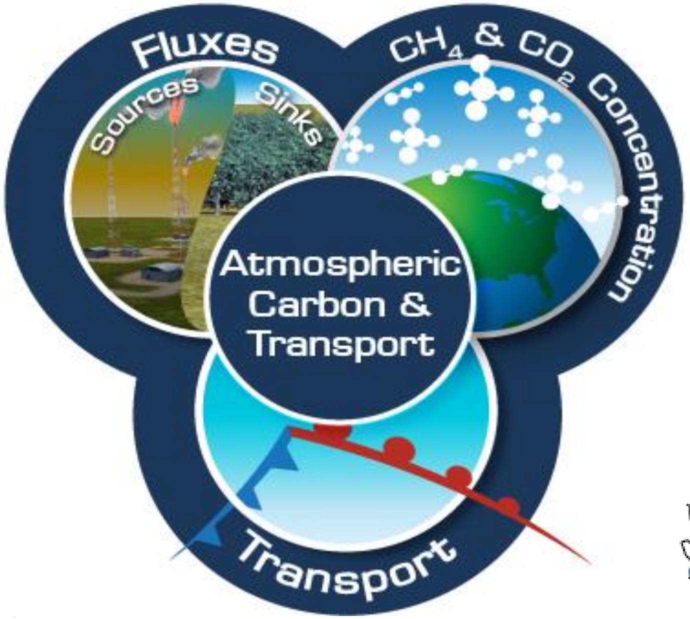
cloud height: 9 km
0.1-s integration time
high SNR & small bias (< 0.1%)
Cloud OD < ~0.4

dawn/dusk orbit, 42W power
other LEO orbits

Summary

- Global/regional atmospheric CO_2 observations require high accuracy and precision measurements owing to very small variations in atmospheric CO_2 mixing ratio.
- Laser absorption lidar at 1.57μm with ranging-encoded IM provides advanced capability in cloud/aerosol discriminations.
- IM-CW lidar has demonstrated the capabilities of precise CO_2 measurements through many airborne flight campaigns under variety of environment conditions, including CO_2 column measurements through thin cirrus clouds and to thick clouds. Over land, clear-sky CO_2 measurement precision within 1-s integration is within 1 ppm while mean bias is much smaller.
- Ranging uncertainties are shown to be below sub-meter level.
- Analysis shows that current IM-CW lidar approach will meet space CO_2 observation requirements and provide precise CO_2 measurements for carbon transport, sink and source studies.

Atmospheric Carbon & Transport (ACT) – America



The ACT-America suborbital mission addresses the three primary sources of uncertainty in atmospheric inversions: atmospheric transport, sources and sinks of carbon, and atmospheric concentration measurements.

Penn State
NASA
LaRC, WFF, GSFC, JPL
Exelis, Colorado State
NOAA ESRL/U Colorado
DOE Oak Ridge, U Oklahoma
Carnegie Inst. Stanford